Light-field based 3D optical tweezers

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Abstract. Optical tweezers are designed to trap nano- and micro-scale particles. Once trapped, it is possible to move the particles but this requires complex mechanical adjustments to the optical system. In this paper, an easier way to trap and move multiple particles simultaneously is proposed, that uses a digital mirror-array and freeform micro-lens-array to generate several steerable optical traps inside a light-field.

1. Introduction

In-vitro fertilization (IVF), among other applications, requires accurate manipulation of very small (nano- to micro-scale) and vulnerable particles that cannot be moved with a direct physical interaction. A well-focused laser beam can behave as a trap for such particles. A standard optical tweezer setup is composed of a laser characterized by a wavelength and maximum power output, a collimation system, a dichroic mirror, a microscope and associated objective with high numerical aperture (NA), as well as a light source and camera for imaging. It is noted in the literature [1] that, if working with spherical beads, two main forces are applied to the bead. One is the scattering force that pushes away beads from the beam, and the other is the gradient force that pulls beads toward the center of the beam. Some approximations based on the size parameter $x = k_m(\lambda, n_m) r_{bead}$ are introduced in [1]. Assuming that $x \gg 1$ allows to express the applied force as function of the bead diameter and laser wavelength, as shown in [2]:

$$F_{grad} = \frac{2\pi n_m r_{bead}^3}{c} \left(\frac{m^2 - 1}{m^2 + 2}\right) \nabla I \qquad (1)$$

where c is the speed of light, m is the ratio between the indices of refraction n_p and n_m of the bead and medium respectively, and ∇I is the gradient of light intensity. Once trapped, the goal is often to move the bead to a certain position or through a specific path. To do so, either the laser source or medium where the beads are placed must be moved. The first process is complex due to adjustments also needed in the focusing system to minimize the loss of light intensity. The second process moves only non-trapped particles, making it impossible to actuate 2 or more particles along different paths. In this paper, we propose a novel and compact optical tweezer system able to catch multiple beads and move them independently, which does not require any mechanical adjustment. This system combines a digital micro-mirror device (DMD) with a freeform micro lens array (MLA). The DMD selected for this research is composed of 1920x1080 micro-mirrors, which can be tilted to produce black-and-white areas in a projected image. The DMD reflects light with a ±12° angle difference from its diagonal. MLAs are patterns of small lenses which have found application in light-field imaging and display [3].

In this research, a freeform MLA is combined with the DMD in order to send discrete rays through the MLA into a specially focused light field (LF), such that they then converge to the position of the optical trap.

The objectives of this paper are (1) to prove that it is possible to trap and move particles with a discretized beam (i.e.: a non-continuous Gaussian beam), and (2) specify the characteristics of an actual system. Section 2 covers the experimental verification of optical trapping with discrete beam, while section 3 proposes the specifications of a LF based optical trap through simulation.

2. Optical trapping with discretized beam

2.1. Experimental setup

Figure 1 shows the experimental setup. A DMD (Texas Instrument *DLPLCR95EVM*) is used to discretize a well collimated λ=450 nm laser beam (Thorlabs *L450-P1600MM*). A high numerical aperture lens (Thorlabs *C330TMD-A*) focuses the discrete rays back into a spot. In this study, the trapped particles are r_{bead}=11.25 µm micro-beads of polyethylene ($n_p \sim 1{,}5$), floating inside a drop of demineralized water ($n_m = 1{,}33$). It was verified that $x \gg 1$ holds under these conditions. A white light source, color filter, microscope and camera are used to track the beads in real-time.

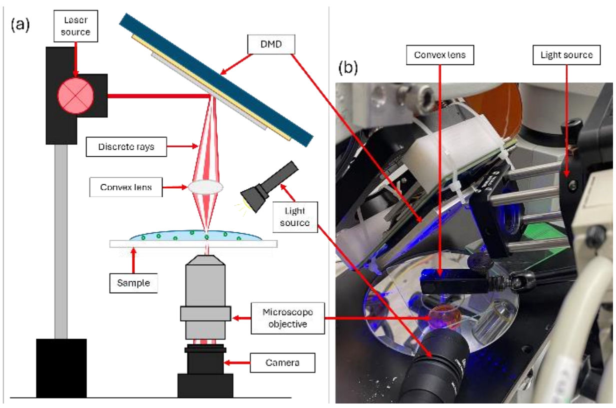

Fig 1. Experimental setup: (a) diagram and (b) actual system used to test the efficiency of optical trapping with a discretized laser beam.

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2.2. Experimental results

Figure 2a shows the discrete pattern applied to the DMD. This pattern emulates the discrete rays that would be used to focus to an arbitrary 3D location within the LF behind a MLA. Figure 2b/2c shows the focused rays and trapped particle within the dashed circle. The circular appearance of the spot indicates that the discrete rays were successfully focused back into a single spot. Next, we seek to determine the force threshold required to hold onto the trapped particle against the overall drift of fluid. This value can then be compared with the theoretical force needed to hold it with a conventional Gaussian beam trap. The experimental parameters are summarized in Table 1.

Table 1. Experimental parameters and results

Parameter	Value
Laser Wavelength	450 nm
Bead radius	11.25 µm
DMD use ratio	1726 pixels (0.08%)
Min. trapping power	3.1 mW
Min. trapping density	2.8 W/mm²
Particle drift velocity	7.95 µm/s

At the focal point, we used a photodiode sensor (Thorlabs *PM16-130*) to measure the minimum light power $P_{beam} = 3.1mW$ to hold onto a trapped particle. Since the average spot size was $r_{beam} = 18.67\mu m$, modeling the power distribution as a cone with base r_{beam} gives a peak intensity h of:

$$h = \frac{3P_{beam}}{\pi r_{beam}^2} \quad (2)$$

The intensity gradient and trapping force applied by the laser are then calculated using equation (1):

$$\nabla I = \frac{\delta h}{\delta r} = 4.55 \;\; 10^{11} W.m^{-3} \quad (3)$$

$$F_{grad} = \;1.5 \;\; 10^{-12} \; N \quad (4)$$

This force is then compared to the frictional force caused by particle drift in accordance with Stokes' law, using the distance travelled from the red to the blue beads within a 7s period to measure the drift velocity V_{bead}:

$$F_{Stokes} = 6\pi\mu_{water}V_{bead}r_{bead} = 1.69 \;\; 10^{-12}N \quad (4)$$

It is thus found that F_{grad} and $F_{stockes}$ have very similar values. This experimental result indicates that discretization of a laser beam into separate rays does not appear to affect optical trapping ability much, so long as the discrete rays are focused back into a spot of intensity similar to a Gaussian beam trap.

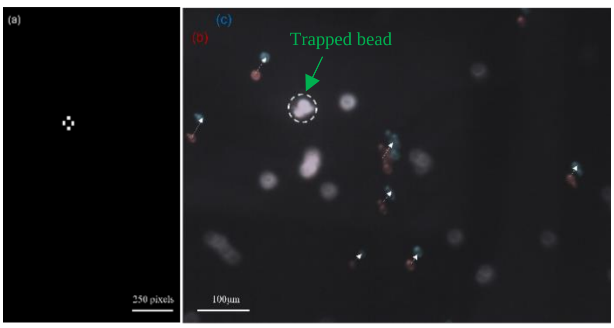

Fig 2. (a) Discrete pattern applied to the DMD, (b) captured image at t=0s, (c) captured image at t=7s.

3. Specification of LF based system

Since conventional MLAs focus light directly behind each lenslet, the output LF is distributed along an increasingly wide area as it propagates. To solve this issue, Fig. 3 shows a freeform MLA design based on a 3x3 array (10x10mm²), which was generated using the inverse ray tracing method [4] in Hyperion™ (Anax Optics Inc.). The resulting LF is concentrated within a 1x1x1mm³ working zone by shifting the focus points of outer segments towards the optical axis. Next, the minimum total laser power (MTLP) is characterized as function of the beam dimension (% MLA). The target beam power and intensity in the LF are fixed as per the experimental values (3.1 mW, 2.8 W/mm²). Ray tracing results are shown in Table 2.

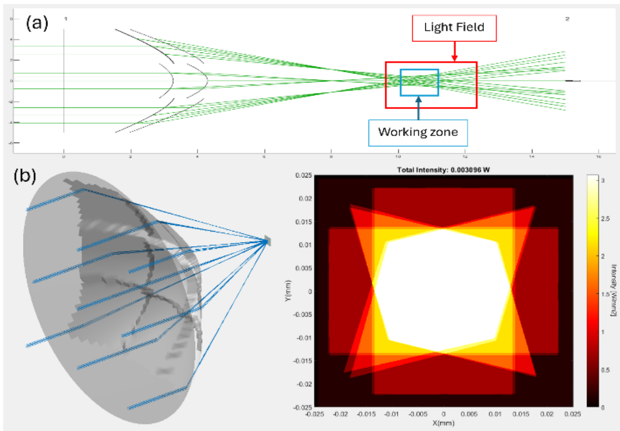

Fig 3. (a) Freeform MLA and focused 1x1x1mm³ LF, (b) Discrete beams combining at a trapping point 10mm away.

Table 2. Ray tracing results

Distance	Light Intensity	% MLA	MTLP
10 mm	2.99 W/mm²	0.68	0.455 W
11 mm	2.81 W/mm²	0.53	0.582 W

Conclusion

Polyethylene beads could be successfully trapped with discrete beams generated though a DMD, when total light power reached 3.1 mW against a drift velocity of 7.95 µm/s. Similar conditions can be reproduced with a focused light-field, generated through a freeform MLA. 3D manipulation of beads with such focused light-field system will be verified experimentally in future research.

References

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